esi® Engineering Bulletin
Electro Scientific Industries
7524 S. W. MACADAM AVE. • PORTLAND 19, OREGON

VOLTAGE DIVIDERS
no. 20

APRIL 1960
REPLACES JUNE 1959

CALIBRATION OF A DECADE TRANSFORMER HAVING ONE PPM LINEARITY

by

N. E. Morrison

Presented as
Conference Paper 59-997
on June 24, 1959 at the

AIEE SUMMER AND PACIFIC GENERAL MEETING

AND AIR TRANSPORTATION CONFERENCE

esi

LITHO IN U. S. A.

CALIBRATION OF A DECADE TRANSFORMER HAVING ONE PPM LINEARITY

N. E. Morrison

In recent years special transformers have been constructed for use as precision decade voltage dividers and as bridge ratio arms. The ratio accuracy of these transformers has reached the 1 part per million (ppm) level. This high order of accuracy, however, makes it difficult to certify the devices.

Various techniques have been used in the past to determine the basic transformer errors at the output voltage taps. W. Sze at the National Bureau of Standards (NBS) has described a capacitance-resistance method of measuring voltage ratio and phase angle.1 C. Pinckney of Hughes Aircraft Co. developed a method for calibrating a voltage divider by a one-to-one intercomparison of its component sections.2 An intercomparison of a group of very stable capacitance standards also has been utilized by people at NBS and the National Standards Laboratory of Australia to calibrate the transformers used in their new capacitance bridges.3,4

The purpose of this paper is to describe a technique which has been used for certifying precision decade transformers to an accuracy of better than 1 ppm at any setting. A minimum of special equipment is needed to obtain this order of accuracy.

A decade transformer having seven place resolution is used to calibrate its own output setting using decades of equal precision resistors as a transfer device.

THEORETICAL CONSIDERATIONS

A decade voltage divider has ten sections of equal impedance. The more nearly equal the various sections are to each other, the more accurate are the output voltage taps. The absolute impedance value of each section need not be known. Only the relative values are necessary for determining accuracy of voltage division.

The midpoint or 0.5 setting of a voltage divider is the easiest to check for tap accuracy. This is the special case for which the impedances above and below the tap are equal. A simple test of symmetry is sufficient to determine the midpoint with very high accuracy. First, the divider to be calibrated is compared against a stable reference divider whose output is matched to the 0.5 setting. Then by interchanging the halves of either divider, but not both, a new comparison is made. The midpoint of the test divider is the average of these two measurements. The decade transformer voltage divider discussed in this paper was tested in this manner. The 0.5 tap agreed with the nominal value to better than 0.1 ppm of input.

If the midpoint of a divider is known accurately, and if there is sufficient resolution and stability in the divider, it is possible to make accurate one-to-one comparisons between equal impedances. A set of equal impedances thus can be intercompared and used to form a reference standard voltage divider. By choosing the proper number of equal impedances one can decide where the voltage taps will occur. It is normally convenient to use ten impedance sections so that the voltage is divided in steps of 0.1. The reference voltage divider is then capable of checking the first decade taps of the original divider. If nine impedance sections are used, the input voltage will be divided in steps of 0.1111111. This combination provides a convenient check for tap errors in the other decades of the test divider. In this manner the midpoint of the test divider actually calibrates the other voltage taps on the same divider with the aid of a set of equal impedances as the transfer device.

DESCRIPTION OF TEST METHODS

Decade Transformer Voltage Divider

The special decade transformer used in these tests was an autotransformer consisting of several individual toroids wound and combined to provide maximum accuracy with minimum interaction between decades. Seven decades of voltage division were provided in the transformer to permit a dial resolution of 0.1 ppm of input. Special switching and winding techniques were used to give a range overlap of ±10% between decades. This greatly reduces the number of dial adjustments for measurements in which a decade setting is near zero and avoids errors ordinarily caused by making step changes in the initial decades. Switching transients were minimized in the transformer by a circuit which keeps the output connected either directly or through a resistor at all times. The decade transformer was the electrical prototype of the Model DT-72 DEKATRAN, manufactured by Electro-Measurements, Inc.

Reference Resistive Voltage Divider

A very stable resistive voltage divider was used as the transfer device in testing the decade transformer accuracy. The resistive divider consisted of ten equal 1000 ohm mica-card resistors connected in series as shown in Fig. 1. Only resistors with a measured temperature coefficient better than 1 ppm/C were used. This allowed measurements to be made without elaborate temperature control. All resistors were encased in the same metal box for ease of shielding.

The unifilar, mica-card construction of the resistors minimizes their series inductance and shunt capacitance. This permits measurements at the test frequencies without need for ac resistance correction. High frequency measurements using capacitance transfer standards have shown that such accuracies are obtainable.

Calibration of the Voltage Dividers

In order to compare each section (R_n) of the resistive divider to a common reference, a separate 1000 ohm resistance standard (R_s) was used. The basic circuit diagram used for the comparison tests is shown in Fig. 2. The decade transformer was used as the comparison arms of the bridge. For small differences between R_s and R_n, the actual difference is 4D, where D is the measured deviation of the transformer from a dial setting 0.5000000. With a bridge input voltage of 6 V rms, detector sensitivity was sufficient to resolve differences of 0.05 ppm of input. This allowed resistance intercomparisons to 0.2 ppm. Terminal linearity of the resistive divider was later calculated from these measurements.

Immediately after resistance comparisons were made, the reference voltage divider was compared directly against the decade transformer. The circuit diagram used is shown in Fig. 3. A divider input of 15 V rms easily provided sufficient signal level to resolve null differences of ±0.05 ppm of input.

Power Supply

A 400 cps generator and isolation transformer were used for all measurements. Each generator output terminal had a capacitance to ground of less than 30 pf, although this was not very critical. The test frequency was 400 cps, because the decade transformer was most accurate near this value. The basic method described in this discussion, however, is valid for other frequencies.

Detector System

The detector circuit consisted of a sharply tuned, high gain amplifier, the output of which was monitored on an oscilloscope. An elliptical display was used, wherein the vertical deflection was connected to the amplifier output and the horizontal sweep to the primary side of the generator isolation transformer. A detector null was reached when phase and magnitude adjustments closed the ellipse to a horizontal straight line. Overall detector sensitivity was approximately 0.3 microvolt.

Phase-Correction Capacitor

In order to bring the phase and magnitude of the two dividers into coincidence for maximum comparison accuracy, it was necessary to make small phase corrections to the resistive divider. This was achieved by using a 100 pf differential air capacitor across the three terminals of that divider. Magnitude variations caused by adding this capacitance were calculated to be less than 0.01 ppm at the 400 cps test frequency.

Shielding and Grounding

All equipment and interconnecting leads in the tests were electrostatically shielded. The shields and decade transformer output tap were connected to the grounded side of the detector amplifier. This kept all cases and signal leads at ground potential and made the effect of ground admittances negligible.

TEST RESULTS

Sample test data are shown in Table I. Results showed that the decade transformer had a maximum linearity error of 0.3 ppm at 400 cps. Although the tests were performed at 400 cps, similar results were obtained at other frequencies. Optimum transformer accuracy in the prototype unit was actually at 200 cps, where linearity error was ±0.15 ppm. However, it is planned to change the optimum point to 400 cps in future units by a reduction of transformer interwinding capacitance.

Although data are given only for tests on the first decade of the transformer divider, the other decades were tested by an extension of the described method. The errors of these decades, however, were less than 0.1 ppm of input at the test frequency.

The principal purpose in the tests was to develop a method which was capable of testing the accuracy of a precision decade transformer having very small errors. Overall accuracy of the system used was estimated at ±0.1 ppm. This is about all that can be expected unless much more elaborate techniques and equipment are used.

There is an added advantage in using resistive elements as the transfer device. This is the fact that they can be tested and intercompared using dc measuring equipment. A set of dc measurements was made on the reference resistive divider. A dc divider with 1 ppm resolution and accuracy was used as the standard. The ac and dc linearities of the transfer divider agreed to within 0.5 ppm in all cases. This very close agreement shows that it is possible to measure the ac linearity of some resistive voltage dividers instead of making a dc calibration. A precision decade transformer such as the one described in this discussion makes an excellent reference standard for calibrating these resistive dividers.

CONCLUSIONS

A method has been developed for the calibration of high accuracy decade transformers, using a set of equal impedances as the transfer device. The exact midpoint of the decade transformer is determined first and then this is used to intercompare a group of very stable resistors. These resistors form a reference voltage divider to check the various output taps on the decade transformer.

Measurements were made at frequencies up to 1000 cps, and data given for 400 cps. Overall system accuracy allows resistor intercomparison to ±0.2 ppm and linearity measurements to ±0.1 ppm of input.

REFERENCES

1. Measurement of Voltage Ratios at Audio Frequencies, Wilbur C. Sze, AIEE Transactions, vol. 76, pt. 1, September 1957.

2. A Method for Calibration of Precision Voltage Dividers, Charles B. Pinckney, Paper presented at AIEE Winter General Meeting, New York, February 1959. (To be published in AIEE Transactions.)

3. The Precise Measurement of Small Capacitances, A. M. Thompson, IRE Transactions on Instrumentation, vol. I-7, 1958, pp. 245-53.

4. New Apparatus at the National Bureau of Standards for Absolute Capacitance Measurement, M. C. McGregor, J. F. Hersh, R. D. Cutkosky, F. K. Harris, F. R. Kotter, IRE Transactions on Instrumentation, vol. I-7, 1958, pp. 253-61.

TABLE I. SAMPLE LINEARITY TEST DATA

Resistor (R_n)	Individual Resistor Error (ppm)	Error Relative To Average (ppm) (±0.2 ppm)	Cummulative Sum of Rel. Error (ppm) (±0.2 ppm)
1	+1.4	+0.36	+0.36
2	+0.8	-0.24	+0.12
3	+5.0	+3.96	+4.08
4	+2.2	+1.16	+5.24
5	+2.4	+1.36	+6.60
6	-0.4	-1.44	+5.16
7	+0.4	-0.64	+4.52
8	-2.4	-3.44	+1.08
9	+1.4	+0.36	+1.44
10	-0.4	-1.44	0
	$10\underline{\vert +10.4}$	0	
	+ 1.04		

Voltage Divider Setting	Resistive Divider Calculated Error (ppm) (±0.1 ppm)	Resistive Divider Measured Error (ppm) (±0.05 ppm)	Difference= Decade Transformer Error (ppm) (±0.15 ppm)
0.0	0.00	0.00	0.00
0.1	+0.04	-0.25	+0.29
0.2	+0.01	-0.30	+0.31
0.3	+0.41	+0.15	+0.26
0.4	+0.52	+0.30	+0.22
0.5	+0.66	+0.60	+0.06
0.6	+0.52	+0.60	-0.08
0.7	+0.45	+0.65	-0.20
0.8	+0.11	+0.40	-0.29
0.9	+0.14	+0.40	-0.26
1.0	0.00	0.00	0.00

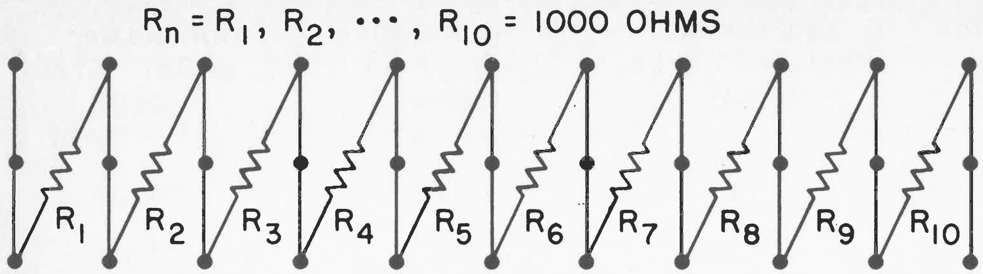

FIG. 1 CIRCUIT FOR REFERENCE VOLTAGE DIVIDER.

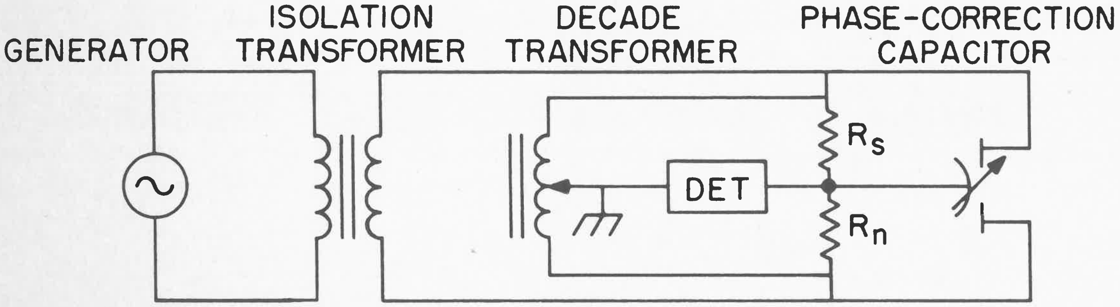

FIG. 2 CIRCUIT FOR COMPARISON OF RESISTORS.

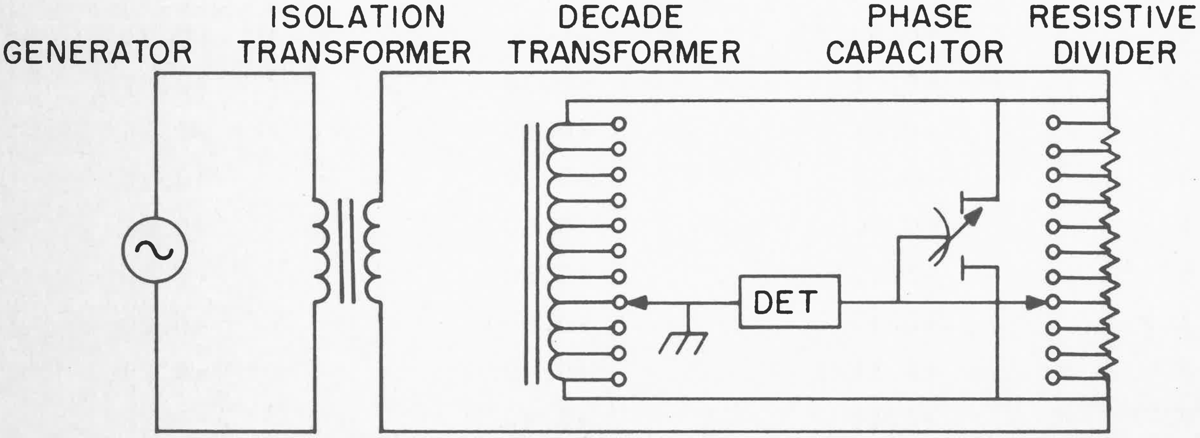

FIG. 3 CIRCUIT FOR COMPARISON OF VOLTAGE DIVIDERS.